Characterizing the Architectures, Diversity and Habitability of Nearby Planetary Systems: The HabEx Observatory

A white paper submitted in response to the National Academies of Science, Engineering and Medicine's Call on Exoplanet Science Strategy

Lead Author: B. Mennesson Jet Propulsion Laboratory, California Institute of Technology
Email: Bertrand.mennesson@jpl.nasa.gov
Phone: (818) 354-0494

Co-Authors:

Summary

Ongoing research, upcoming developments in ground-based facilities, and the launch of new space missions (Transiting Exoplanet Survey Satellite [TESS], James Webb Space Telescope [JWST], and Wide Field Infrared Survey Telescope [WFIRST]) will continue to advance knowledge of the variety and nature of exoplanetary system components over the next decade and a half. However, many key questions will remain: What is the architecture and full diversity of mature planetary systems? What is the linkage between individual planet properties, planetary system architectures and circumstellar dust structures? How diverse are planetary atmospheres over the full range of planet sizes and stellar insulation levels? Are there Earth-sized planets orbiting in the habitable zone (HZ) of nearby sunlike stars, with water vapor in their atmospheres, evidence for surface oceans and signs of life? Are these signs of life really of biotic origin? Answering all of these questions requires direct imaging and spectroscopy from space in reflected light and/or thermal emission. We exclusively discuss reflected light (near ultraviolet [UV] to near infrared [IR]) investigations, identifying some of the observational, technological, and theoretical challenges that must be met to accomplish such a feat. This paper concentrates on one possible implementation strategy currently under study: the HabEx (Habitable Exoplanet) Observatory mission concept.

1. Limitations of currently planned and future exoplanet characterization missions

With thousands of known exoplanets, astronomers have discovered entire new types of planets (from super-Earths to sub-Neptunes) and planetary systems (compact multiple object systems), all mostly derived from planet sizes, masses, and orbits. A current driving interest is exoplanet characterization by way of atmosphere studies, especially for small rocky planets that might support life. So far, this incredible endeavor is focused on planets orbiting M dwarf stars, and thus the current state of the art and next decade is limited to rocky planets around M dwarf stars. The small host star (10–50% the size of our Sun) makes a much greater signal for any planet-finding technique, especially indirect ones. Yet the low luminosity of M dwarf stars means planets are very close to the star, and likely tidally locked, to be at habitable temperatures. The past and present UV and high-energy flaring events typical of M dwarf stars also create radiation environments much higher than Earth's. JWST will perform transmission spectroscopy of atmospheres of exoplanets down to small rocky worlds with a handful in the host star's HZ, but a thin atmosphere superimposed on a star the size of the Sun is too weak of a signal and out of reach. The large ground-based telescopes under construction with second-generation instruments anticipated to be online in the late 2020s will directly image dozens of mid M dwarf stars searching for orbiting Earth-sized planets, but instrument contrast of 10^{-7} to 10^{-8} suitable for M dwarf stars still leaves Earth-Sun analogs at 10^{-10} out of reach. TESS will have completed its all-sky transit survey of stars within a few hundred light years and Plato may have launched. The planned microlensing with WFIRST will have uncovered thousands of exoplanets above Mercury mass, dramatically extending the exoplanet census from Kepler's 0.01 to 1 AU semi-major axis, to orbital separations from 1 AU out to infinity (i.e., including free-floating planets), but will not provide any spectroscopic capability nor image all planets in a given system. Radial velocity (RV) surveys will continue to contribute more detections of massive planets in long-period orbits and push the current ~1 m/s accuracy limits down to access lower mass planets than presently possible around sunlike stars. **However, only space-based direct imaging can meet the science goals of dynamically and spectrally characterizing exo-Earths in orbit around sunlike stars and explore their full planetary systems' context.**

2. HabEx top-level exoplanet science goals and requirements

NASA is currently funding four parallel concept studies for potential future flagship missions in preparation for the upcoming Decadal Survey in astronomy and astrophysics. Two of these studies, HabEx and LUVOIR (the Large UV Optical InfraRed surveyor), share the same overarching goals for exoplanet science: **characterizing exo-Earths around nearby sunlike stars in reflected light, studying habitability and biosignatures in their atmospheres, and getting family portraits of most, if not all, planets and interplanetary dust structures in these systems.** While they differ in their proposed implementation, exact observing strategy, and levels of ambition (LUVOIR aiming for a larger sample of exo-Earths), both mission concepts require unprecedented levels of starlight suppression at very small angular separations and share a number of requirements. We concentrate here on the HabEx concept[*], which is currently based on a 4 m, off-axis, ultra-stable UV/optical telescope (architecture A). HabEx is primarily optimized for exoplanet observations, but also aims at executing a broad range of general astrophysics and solar system studies.

In order to directly detect an Earth twin seen at quadrature around a solar analog at 10 pc for instance, a stable starlight suppression level of <~ 10^{-10} at <0.1" from the star is required. While small inner planets set the most demanding requirements on contrast and spatial resolution, characterizing Jovian analogs in the nearest, most favorable systems sets a separate high contrast field of view of ~2" or more around the star. Figure 1 shows this performance goal in the context of existing and planned high-contrast direct imaging instruments. It clearly illustrates that a quantum leap in performance is required over the current detection limits, which only enable the observations of bright (self-luminous) giant exoplanets with flux ratios of $\sim 10^{-5,6}$ at separations >0.5". The WFIRST coronagraph instrument and technology demonstration would provide a major stepping stone in that direction (see white paper by Vanessa Bailey[1] for details), but no current or planned facility will provide the full necessary improvement. Given the top-level science goals, we further derive *some* of the main requirements driving HabEx exoplanet instrumentation and overall survey strategy.

2.1 Exo-Earth direct detection and orbital determination requirements

Assuming that no precursor (e.g., high precision radial velocity or astrometric) detections of exo-Earths are available prior to launch, HabEx (or LUVOIR) would have to carry out a broad survey of nearby stars to find Earth-sized planets and confirm that they are orbiting in the HZ. **Based on simulations of orbit fitting, four well-spaced HabEx broadband detections with 5 mas rms position uncertainty each are required to achieve 10% precision on the three key orbital parameters: semi-major axis, eccentricity, and inclination**. Once these parameters are established with that accuracy, the main remaining uncertainty on planet size comes from the radius–albedo degeneracy. Using broadband photometry alone, planet size can be constrained to within a factor of 4 (e.g., assuming a generous 0.06-0.96 range in albedos). **In the case of an Earth twin, detailed atmospheric retrieval studies of a wide enough visible spectrum (at least covering 450–700 nm) at sufficiently high spectral resolution (R>70) and signal-to-noise ration (SNR; >10)** yield uncertainties in planetary radius of <50%.[2]

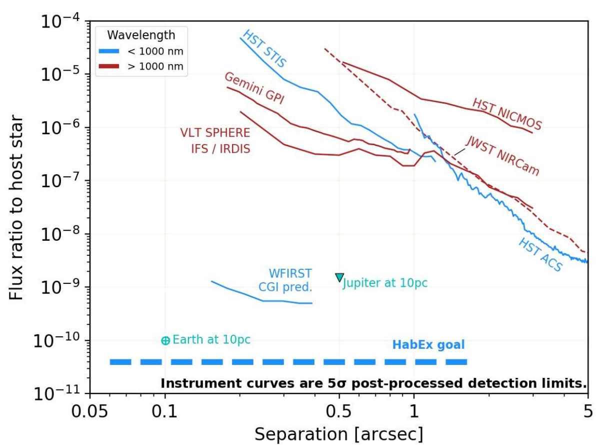

Figure 1: HabEx performance goal and expected exoplanet yield, in the context of existing and planned high-contrast direct imaging instruments, illustrating that a quantum leap is required to directly image and characterize exo-Earths around sunlike stars. Figure courtesy of V. Bailey, T. Meshkat, and K. Stapelfedt.

[*] An iterim report of the HabEx concept study will be posted at www.habex.jpl.nasa.gov and/or at the NASA 2020 Decadal survey preparation website by mid 2018.

Previous studies[3] also show that the shape and strength of reflected light atmospheric spectral bands encode information about the planet's surface gravity and the atmospheric scale height, with constrain information about the planet radius.

2.2 Detecting water, searching for signs of life and constraining their origin

Exoplanets having atmospheric water vapor show a series of broad spectral absorption features from 0.8 to 2 μm. HabEx's detection of at least one of the water vapor spectral features would securely identify water vapor on the planet's atmosphere. Detailed measurements of multiple water vapor features will provide constraints on water vapor atmospheric abundances. Thus, HabEx will need to at least able to detect **water at 820 nm and 940 nm (i.e., provide a spectral resolution R>35 at an SNR>10** over that interval).[4]

While the detection of water vapor would be very interesting, the presence of liquid water oceans at the surface would be even more compelling. It can first be inferred through the polarization that liquid surfaces imprint on reflected light, which is expected to generate a significant (~20%) broadband flux enhancement in one linear polarization vs. the other. These polarimetric features are typically maximum around a 45 deg illumination phase, and thus, HabEx is required to provide a **polarimetric capability and reliably detect a 20% polarization effect of that magnitude, corresponding to a 4×10^{-11} excess flux ratio** for an Earth around a sunlike star. A second effect from water oceans is glint (specular reflection), which can be detected as a large increase in the planet brightness of a planet in a crescent phase.[6,7] As illustrated in Figure 2, in the case of the Earth, this effect is seen at illumination phases greater than ~120 deg and also results in an apparent reddening of the planet. **The requirement placed on HabEx here is the ability to conduct broadband multi-epoch observations and access illumination phases at ~120–150 deg** at which the expected flux ratio (without ocean glint) would only be 4×10^{-11}.

The search for life fundamentally requires two related sets of investigations: a search for the gases attributable to life, and characterization of the environment in which those gases arose (see white paper by Shawn Domagal-Goldman[8]). One of the most significant and most detectable signs of life in modern Earth's atmosphere is the presence of large quantities of atmospheric molecular oxygen. Molecular oxygen has a strong spectral feature at 760 nm, and leads to the accumulation of ozone in the atmosphere, which has a strong cutoff feature short of 330 nm and a shallow feature at 550 nm. **HabEx is designed to detect features from both of these gases, which drives its spectral range down to**

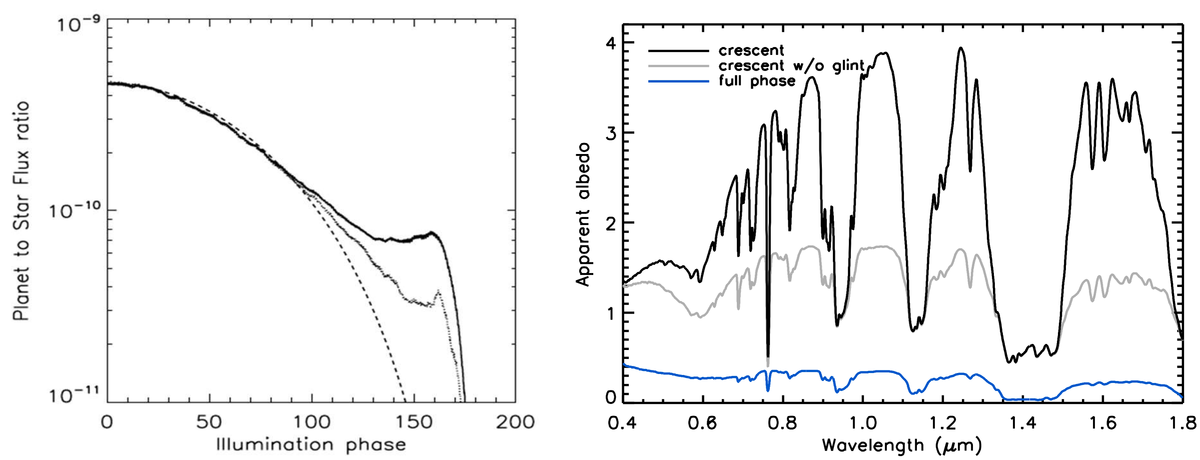

Figure 2: Illustration of the glint effect due to surface water oceans on the Earth.[6,7,5] *Left*: observed brightness enhancement in the 1–1.1 mm region due to ocean glint (upper curve) relative to a pure Lambertian phase scattering function (lower curve). The effect is clear for illumination phases above ~120 deg. *Right*: illustration of spectral dependence of the glint effect at a given phase. Apparent albedo of Earth at full phase (blue) and at crescent (150 deg) phase both with glint (black) and without glint (grey). Values larger than unity imply forward scattering.

300 nm, with a minimum spectral resolution R>70 to detect the O_2 feature at 760 nm.

Fundamentally, the same bulk atmospheric phenomenon is at the heart of all the known false positives for O_2 and O_3: a high O/H ratio in the planet's atmosphere. If that ratio can be constrained, then all the known false positive generation mechanisms can be eliminated. There are two molecules HabEx has the ability to detect that could provide such constraints: H_2O and CH_4. HabEx would be able to rule out such mechanisms by detecting multiple H_2O features from 0.8 to 1.8 μm, Given that these features become broader and deeper from 940 nm to 1,130 nm to 1,410 nm (e.g., Ref. 4), there is a strong desire to **extend the HabEx wavelength range in the IR to ~1,500 nm**. Similarly, while multiple methane features are known in the Earth visible spectrum, a much stronger feature is found around 1,690 nm, and would provide the best constraints on methane abundance (~10× the Earth level). **The detection of these near-IR features drives HabEx upper wavelength range to a minimum of 1,700 nm, with a minimum spectral resolution of 20.**

2.3 Characterizing the full diversity of exoplanetary systems, in terms of overall architectures and planet characteristics

A separate white paper is dedicated to this question.[9] This goal requires the broadest possible wavelength range, overlapping with spectral features from key atmospheric species (be ready for anything!) and a high-contrast field of view as large as possible. The latter is necessary to fully explore the linkage between individual planet properties, planetary system architectures, and circumstellar dust structures, and be able to see all of these components in the most favorable nearby systems. We hence set here a minimum field of view requirement of 2"×2" for high-contrast imaging.

3. HabEx implementation and observing strategy

Table 1 compares the overall requirements derived above (in terms of flux ratio detection limits, high contrast field of view, spectral range and spectral resolution) to HabEx expected performance and specifications. **Missing short table with these four design parameters with requirements on the left, and specs on the right]**

The HabEx exoplanet observational strategy is based on a dual starlight suppression system, capitalizing on the relative strengths of each system. It first uses a nimble coronagraph to search for planets around ~120 stars, conducting an average of ~7 visits to each in order to increase detection completeness and determine orbits via multi-epoch broadband imaging at visible wavelengths. The currently baselined HabEx coronagraph is a charge 6 vortex coronagraph. It was selected for its high resiliency to low order telescope aberrations and high planet throughput, two characteristics that go hand-in-hand with the choice of an unobscured monolithic aperture (4 m off-axis primary). The second starlight suppression system is a large external starshade flown 120,000 km in front of the telescope to block starlight before it even enters the telescope. The starshade provides very sensitive and ultra-broadband spectroscopy at small angular separations, covering for instance the full 300–1,000 nm range at once, at a wavelength independent "inner working angle" (closest detectable exoplanet separation) of 60 mas. *Key technologies required for the successful operation of such high-contrast coronagraph and starshade systems are detailed in the white paper of Brendan Crill et al.*[10]

4. Projected science yield and uncertainties

Using new exoplanet yield estimation methods,[11] the quantity and quality of exoplanet science (hereafter "primary science yield") that the HabEx mission concept could produce in some illustrative important cases has been estimated: visible broadband detection, orbit determination, and spectral characterization of different types of planets, including HZ Earth-like planets, over the full 0.3–1.0 μm range. Figure 3 shows the nominal number of exoplanets expected to be detected during HabEx broad coronagraphic survey (2 years), using the default occurrence rates derived from Kepler data (Exoplanet Program Analysis Group's Science Analysis Group-13, "SAG-13"), a constant exozodi level of 3 zodis

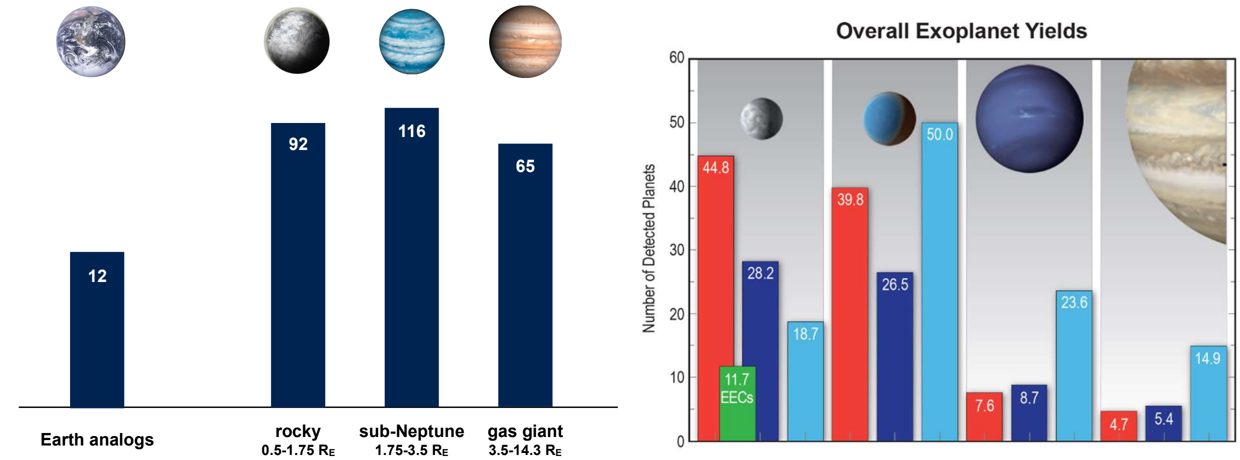

Figure 3: Predicted HabEx yields using nominal SAG 13 occurrence rates estimates. EECs are "exo-Earth candidates," i.e., Earth-analogs in the habitable zone, with radii in the 0.6–1.4 Re. All detected planets have their orbit measured via multi-epoch imaging. All EECs will have at least one 300–1,000 nm spectrum measured.

per star, and the planet classification scheme by Kopparapu et al.[12] Using these assumptions and instrument performance models consistent with detailed telescope and coronagraph design specifications, it is estimated that HabEx will detect and characterize the orbits of 92 rocky planets (radii between 0.5–1.75 Re), among which ~12 Earth analogs, 116 sub-Neptunes (1.75–3.5 Re) and 65 gas giants (3.5–14.3 Re).

Based on the orbital parameters measured by the coronagraph, starshade slews will be timed to get broadband images and 300–1,000 nm spectra (with R=140 from 450–1,000 nm) of all systems with Earth-analogs (EECs) found, and of all other planets visible at that epoch in these systems. In select favorable systems, the starshade may be moved to get muti-epoch visible spectra or extend coverage to the near IR (1,800 nm) and/or the near UV (200 nm). Figure 4a–b illustrates one of these starshade observations in the favorable case of a nearby 5-planet system, with an earth analog, a sub-Neptune, Saturn, Jupiter, and Neptune analogs. With a total of about 100 starshade slews available, 300–1,000 nm spectra will also be obtained for at least half of the many systems with no Earth analogs found by the coronagraph, providing 100+ detailed spectra of the other types of planets present in these systems.

Conclusion

As part of the on-going HabEx Observatory concept study, we have conducted a detailed analysis of the direct imaging and spectroscopic capabilities required to characterize in detail the architectures, diversity and habitability of nearby (<20pc) mature planetary systems. We found that a 4m off-axis high throughput UV-optical telescope equipped with a dual (coronagraph +

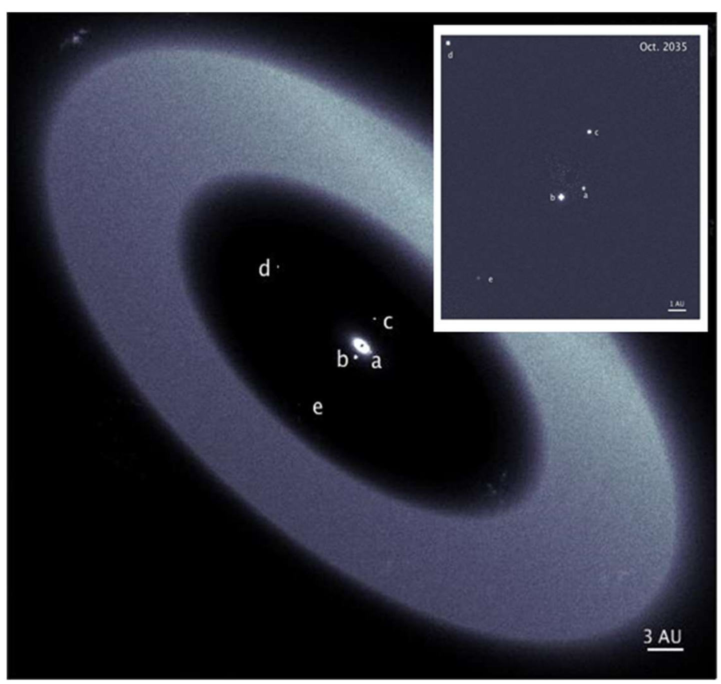

Figure 4a: Simulated starshade image.

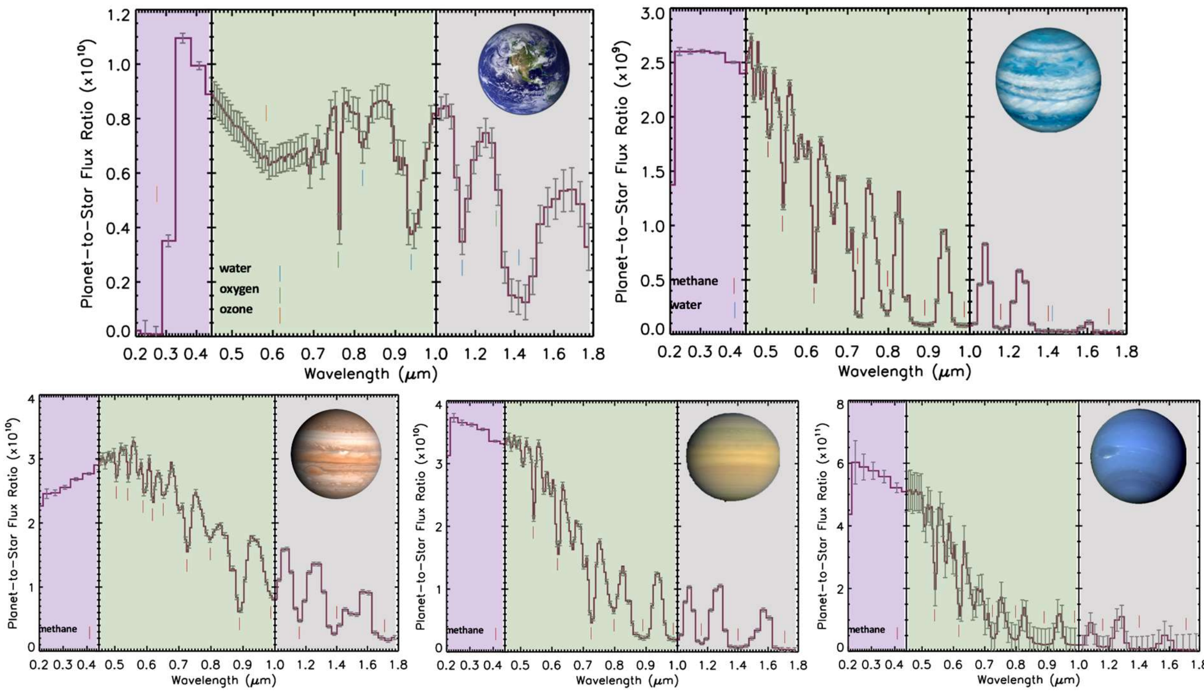

Figure 4b: Simulated spectra of individual planets.

starshade) starlight suppression system provides exceptional capabilities. With nominally over 90 rocky planets 250 planets directly detected around sun-like stars for the first time, among which over 90 rocky planets, most of them with orbits determined and spectra measured over a minimum wavelength range of 300-1000nm, the HabEx observatory will revolutionize our knowledge of planetary science. At the same time, it would provide a dozen spectra of possible Earth analogs, with the ability to search for signs of life int ehier atmosphere and assess their biotic origin via near Uv to near IR spectroscopy. We find that the hybrid (coronagraph + starshade) approach takes full advantage of the complementary strenghs of each system. It also allows maximum flexibility to adapt the observing strategy to unavoidable astrophysical sources of uncertainties, and provides a more robust architecture overall. The nimble -easily repointed- coronagraph brings breadth to the HabEx exoplanet search and orbital determination phase, while the high throughput inherently broad-band starshade system provides in depth spectral characterization at the small angular separations required, all the way to the near infrared.

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